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POPULAR EXPOSITION

OF

THE EFFECT OF FORCES

APPLIED TO

DRAUGHT.

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Fig: I.

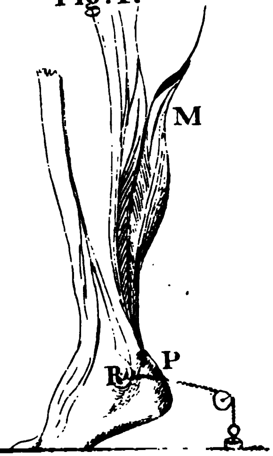


Fig: II.

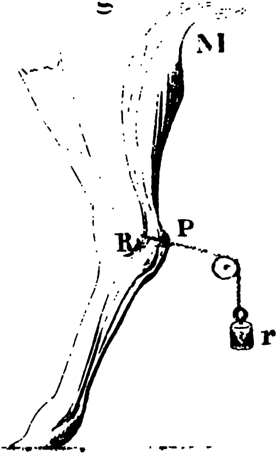
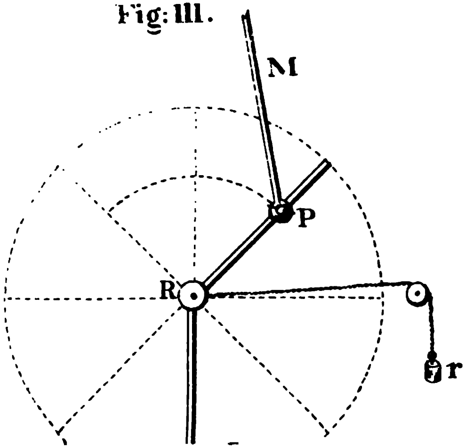


Fig: III.



A

POPULAR EXPOSITION

OF

THE EFFECT OF FORCES

APPLIED TO

DRAUGHT.

WITH ILLUSTRATIONS OF THE PRINCIPLES OF ACTION, AND TABLES OF THE PERFORMANCE OF

HORSES AND OF LOCOMOTIVE ENGINES

ON

RAILWAYS.

AND AN APPENDIX,

CONTAINING THE RESULTS OF SOME EXPERIMENTS ON

FRICTION.

By DAVID RANKINE, Esq.

Father of Professor W J Macquorn Rankine C.E. L

"....axiomata illa vera, et solida, et viva, in quibus humanæ res et fortunæ sitæ sunt."—Bacon.

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CONTENTS.

Page
Of the Resistance to Draught on Level Roads, or Friction, ... 5
Of the Mechanical Advantage derived from Wheels, 10
Of the Mechanical Advantage on a Railway, 14
Of Horse Power, ... 18
Operation of Horses upon Railways, . . 25
Table I. of Horse Power, by the Formulæ of Wood and Leslie, ... 21
Table II. of Horse Power, by the Author's Formula, ... 22
Table III. Comparative View of the results of Practice, and those of the Author's Formula, . 24
Table IV. Operation of Horses on Level Railways, 25
Table V. Operation of Horses on Inclined Railways, ... 27
Table VI. Performance of Horses in Light Draught on Inclined Railways, ... 30
Of Locomotive Engines, ... 33
Table of Performance of Locomotive Engines, 41
Speed of Locomotive Engines, ... 42
Appendix, ... 69

A

POPULAR EXPOSITION

OF

THE EFFECT OF FORCES APPLIED TO

DRAUGHT.

OF THE RESISTANCE TO DRAUGHT ON LEVEL ROADS, OR FRICTION.

If a level surface were perfectly smooth and free from obstacles, a body resting upon it would oppose no resistance to horizontal motion, how heavy soever it might be. On such a surface a ship of the line would yield to the power of a child, as a planet is deflected from its usual orbit by the slightest adventitious force. It is superfluous to say that such a surface cannot exist in nature; but it is not so to add that it is the business of all road-making to approach to it as nearly as possible.

All surfaces are more or less covered with obstacles, consisting generally of particles or portions of the matter composing them; which either lie loosely and irregularly, as stones upon a common road; or, forming the superficial particles of a homogeneous aggregate, they present a fixed and uniform array, as on the surface of an iron rail, however smooth it may appear. It is of little importance to our present subject to form conjectures concerning the shape of the obstacles on surfaces of the latter description, where they are nearly beyond the perception of our senses: it is of no consequence whether we suppose them spherical, with Parent; or angular, with Euler: all that we are concerned in, is their effect in forming resistance to Draught, and the laws of their operation in so doing.

The resistance to the motion of bodies, arising from the obstacles on surfaces, is termed, Friction. When two surfaces are rubbed together, it is plain that the friction opposed to their sliding upon each other will be, in the first place, proportionate to the height of the obstacles upon them, or their degree of roughness; and, in the second place, to the amount of force that is applied in pressing the surfaces together, and consequently interserrating their obstacles, or causing them to crush or grind each other in the attrition. The above is termed *Sliding Friction* or *Friction of Attrition.* There is another description of friction called *Rolling Friction*, which is the resistance attending the rolling of a cylinder, or cylindrical wheel, over a level surface. This also is in proportion to the weight of the rolling body: but of it I shall take further notice, when treating of wheels. There is a third kind of friction; but of this, as it has nothing to do with the subject of the essay, I refer the reader for farther notice, to the Appendix.

Friction, then, is the product of the gravity or weight of bodies in Draught, and the obstacles on the surfaces or roads on which they are drawn. Now the gravity or pressure of any weight upon a surface is equal in equal times, whatever may be the extent of surface over which it is drawn in such times: which means that if it be drawn over one foot of surface in one minute, over two feet in the next minute, and over three feet in the third minute, its pressure on each point of the surface will be one half in the second minute, and one third in the third minute, of what it was in the first.*

From this it follows that, on a homogeneous surface, the friction of a body moved is equal in equal times;

---

* A familiar example of this law is afforded in the case of boys sliding on ice; when they may frequently be seen to slide or run rapidly over pools, on which, if they walk or stand still but for an instant, the ice gives way with them.

or it diminishes in relation to the space described, as this increases in relation to the time occupied.*

This law of friction has been established by the experiments of Vince, Coulomb, Amonton, and others, and its results must be esteemed as of the highest interest and importance; for it follows necessarily, that a power operating in draught has the same amount of friction opposed to it in a given time, how great soever the extent of space moved over in that time: and hence if any power were constant at all velocities, like that of a weight descending towards the earth, it would be capable of accelerating indefinitely the speed of any draught that it could set in motion, provided there were no resistance from the atmosphere or other cause, besides the friction of its draught on a uniform surface. But no such power can exist either in animals or in machines.

When such authorities are named as Coulomb and Vince, a simple statement of the foregoing law might well be thought sufficient. But as I know that doubts are still entertained on this subject, at least with respect to the friction of wheel carriages, I shall add the results of some experiments that were made by myself on the friction of wheel carriages; and also those of a few relative to the friction of machines. In this place, however, I shall only state, that I found the results of my experiments concerning wheel carriages, to be, without exception, confirmatory of the law above laid down; and I refer the reader to the Appendix for a description of the method by which they were obtained.

---

* Hence horses as well as men discover from experience that, when a particularly soft and difficult pass occurs on a road, their draught is brought through it with much greater ease if they increase their speed; for the shorter the time spent in moving over it, the less is the depth to which the wheels sink.

Numerous experiments have been at different times made on the friction of wheel carriages on railways, by persons employed at collieries; and the results of these experiments have always conformed to the above law; but with the exception of some that were made by Mr N. Wood with a dynamometer, the moving power employed has been the gravity of the carriages themselves, operating in their spontaneous descent of inclined planes. Now, however conclusive and satisfactory such experiments may be deemed by those to whom subjects of natural philosophy are familiar, to some the idea may seem rather confusing, that the power and the resistance should be embraced in the same body. In mine there was no such source of incredulity, for the power was that of a weight descending from a pulley; and though the scale of the experiments was thus necessarily limited, they will perhaps be viewed as the most convincing by the superficial observer.

OF THE MECHANICAL ADVANTAGE DERIVED FROM WHEELS.

WERE it not for the friction upon roads, wheels would be quite unnecessary, and all carriages might be employed like the sledges that are used on ice and frozen snow. When a wheel is employed to give mechanical advantage in the raising of a weight, by a rope winding round its axle, it operates as a system of levers, by which the advantage of the power over the weight is as the diameter of the wheel to that of the axle: here the velocity of the power must bear also the same ratio to that of the weight, and this is a disadvantage. But when the wheel is applied to a carriage, its effect becomes a sort of mechanical paradox; for the same advantage that is gained by it in power is also gained in velocity; it causes the weight to move with the same speed as the power, or it increases the speed in the same degree that it diminishes the resistance. If the bottom of a sledge were similar in surface to the axles generally used, and if it were drawn along a road similar in surface to the axle boxes of wheels, and having the same unguent applied, then would the amount of its friction be precisely the same as that which takes place between the axles and the boxes of wheels. The degree of this friction varies with the different materials of which axles and boxes are composed, and with the different unguents that are applied to them: it has been found to amount to about $\frac{1}{15}$ of the weight of the body drawn, and to less and more according to circumstances. But whatever be its quantity, it is plain, that, when a carriage moves upon wheels, the space over which each axle rubs in its box in a given time must be as much less than that through which the carriage moves in the same time, as the circumferences of the wheels are greater than those of the axles, or the diameters of the wheels than the diameters of the axles; for the space described by the carriage is that rolled over by the wheels, and one revolution of the wheels is attended with one revolution of the axles. If the friction, then, of the axles without wheels would, in rubbing over a surface similar to that of their boxes, be equal to $\frac{1}{15}$ of the weight of the carriage, the friction, by the application of wheels of 15 times the dimensions of the axles, would be reduced to $\frac{1}{15} \times \frac{1}{15} =$ the $\frac{1}{225}$ part of the weight of the carriage; or with respect to the friction of axles, the resistance of the carriage on a level would be to its weight as 1 to 225. 1 pound of power becomes thus equal to 225 pounds in draught; or the mechanical advantage derived from the wheels is as 225 to 1.

The wheel has, however, to overcome also the rolling friction of its own circumference on the ground. In this again it operates as a system of levers; and that point of its circumference which meets the ground, or any obstacle upon it, becomes the fulcrum, while the centre is always the point at which both the power and the resistance are applied. Now if any obstacle on the ground, as (O, Fig. 5,) is so high, that the right line C L, passing from the centre of the wheel to the point at which the circumference meets the obstacle, and representing the lever, forms equal angles with the line of application of the power C A, and with the line of the loads bearing C F, then are the advantage of the power and that of the load in a state of equality; and the power must consequently become at least equal to the whole pressure of the load upon the wheel, before it can drag it over such obstacle: and in every case the advantage of the power from the wheel, is to that of the load, as the angle A C L to the angle F C L, or as the sine of A C L to the sine of F C L. The mechanical advantage derived from wheels is thus greatly modified by the nature of the roads on which they are employed, and as the height of an obstacle always forms the difference between the sine of the angle A C L, and sinus totus, when the bearing of the power is horizontal; it becomes eligible, on rough roads and pavements, to have the bearing of the power, or the line of draught, rather elevated from the wheel's centre, even, though, to attain this, the height of the wheels must be diminished, and the friction of axles increased. By our increase of skill in road making, and in the construction of wheels, considerable mechanical advantage has been obtained over the resistance of friction. It is, however, remarkable, that although progressive improvements had been made upon wheels, it seems to have been scarcely imagined, till the time of Macadam, that something was still to be gained on stone roads by the removal of the *obstacles* themselves, as well as by the improvement of the means of surmounting them. The friction of coaches and carts upon stone roads, has been commonly considered as equal to about $\frac{1}{30}$ of the draught,* and thus the mechanical advantage becomes as 30 to 1. On the best Macadam roads, however, I should conceive the friction to be not more than $\frac{1}{35}$ of the draught, when the road-metals are in a solid state; or the mechanical advantage as 35 to 1.

---

* The draught is always understood to include the weight of the carriages.

OF THE MECHANICAL ADVANTAGE ON RAILWAYS.

On a railway the rolling friction of wheels may be viewed as nearly altogether destroyed, for the lever is then always represented by the line C F, (Fig. 5.) with the fulcrum continually at F; and as C F is here also the line of bearing of the load, the leverage of the load becomes nothing; at the same time the advantage of the power is the greatest possible, for its line of bearing A C, is, or ought to be, nearly at right angles to the lever C F. The friction on a railway then consists solely of that of the axles of wheels.

The mechanical advantage on a railway has been generally considered as about 7½ times that upon a common road; say, 30 × 7½ = 225: thus 1 pound of power will drag 225 pounds, or a horse will drag on a level railway 225 times the weight with which he pulls. The friction of carriages on railways has been variously stated by different individuals, but Mr Nicolas Wood, an engineer of great experience in such matters, states, in his " Treatise on Railways," that on edge rails the friction of carriages, such as are generally employed, having wheels from 11 to 13 times the dimensions of their axles, is seldom less than $\frac{1}{219}$ of the draught; and he considers $\frac{1}{200}$ as about an average. As this agrees closely with the result of my own observations, I shall adopt $\frac{1}{200}$ as the proportion of friction to any draught on a level edge rail; 200 to 1 then becomes the mechanical advantage of any power upon a level railway. Hence 1 pound of power will drag 200 pounds. A horse will drag 200 times the weight with which he pulls; and universally, the draught of any power on a level railroad is equal to the power multiplied by 200.

The friction or resistance of any load upon a level being determined, I shall now point out the degree in which the resistance is augmented when a level is departed from, and a draught is brought to ascend an inclined plane.

When a body is placed on an inclined plane, it has, by the law of gravity, a tendency to descend the plane. This force of gravity bears just the same proportion to the whole weight of the body, that the height does to the length of plane. Were there no such thing as friction on an inclined plane, any heavy body would spontaneously descend it, how slight soever the degree of inclination; but in the actual state of things, a body will be at the point of spontaneous descent only when its gravitating impulse becomes equal to its resistance of friction on the plane.

It is thus evident, that in the ascent of a slope we have the friction and gravity of a draught acting in conjunction to form resistance to its motion, but that in descending we have them in opposition to each other; the friction remaining, as in all cases, a *resistance*, while the gravity becomes an *impelling agent* down the plane.

It is as a resistance that we are at present to view the gravity of a draught. In order to find the amount of this resistance, we have to multiply the given draught by the elevation of plane, in fractions of its length. For example:—a draught of 1000 pounds on an inclined plane of 1 in 100, has a resistance of gravity $= 1000 \times \frac{1}{100} = 10$ pounds.

On an inclined railway, the whole resistance of any draught consists of its gravity added to its friction, or $(G + F.)$

The friction of a load is diminished in proportion to the elevation of plane; but this is too trifling a quantity to be taken into account in practice. (F) may therefore be esteemed a constant quantity $= \frac{1}{200}$ of the draught, while G varies with the elevation of plane; and the resistance (R,) of any draught (D,) on any inclined plane (E,) is always $R = F + \overline{D \times E}$. When the power employed on a railway is not susceptible of increase, the draught to be adjusted to any elevation must evidently be diminished in the same proportion in which its resistance would be increased, if it were placed on the inclined plane; thus, if a horse fully loaded on a level were to arrive at a slope on which the resistance of his draught would be doubled, he could ascend with only one-half of such draught.

The general rule for adjusting the draught of any power to any elevation will consequently be, to multiply the draught on a level by its friction, and divide the product by its friction added to its gravity—the whole resistance it would have on such elevated plane. Adopting the initial letter of each term we may state the rule thus

RULE 1st. $D \times \frac{F}{F + G} = D\ Q$ or draught required.

The following rule for ascertaining the draught of any power at any elevation, and with any amount of mechanical advantage, is more comprehensive and simple in the working. It may be stated—

RULE 2d. $P \times \frac{M\ A}{1 + (M\ A \times E)} = D\ Q.$

P is the power employed; D Q, the draught required; E, the elevation of plane; M A, the mechanical advantage of a power expressed by 1.

On a railway M A being equal to 200, this formula is always $\dot{P} \times \frac{200}{1 + (200 \times E)} = D\,Q.$

HORSE POWER.

The rules for estimating the effect of any power being given, our next step shall be to investigate the operation of horses when they are employed as the moving agents in draught.

We have very different accounts of the power of horses from different individuals: this, indeed, is little to be wondered at, since there is not only great variety in the sizes, but also in the breeds and crosses of these animals, attended with nearly equal variety in power, speed, and energy. The power of a horse is stated by Watt to be = 150 lbs. at the speed of 2½ miles an hour—by Desagulier, 200 lbs. at 2½ miles an hour during 8 hours—by Hachette, 140 lbs. at 2⅓ miles an hour—by Smeaton, about 150 lbs. at 3 miles an hour during 8 hours—by Mr James Jessop, London, at from 4 to 5 cwt. for the greatest power, and 150 lbs. for daily work; and Mr Josias Jessop saw a horse, with his greatest exertion, drag 4½ cwt. out of a pit, by means of a rope over a pulley.

But by far the most satisfactory, because the most circumstantial, information on this subject, is given by Mr N. Wood, in his treatise, already noticed. After much observation and numerous experiments, Mr Wood found, as an average, that a horse, weighing about 10 cwts. is capable of dragging on a railway, 10 tons; or of exerting a power of 112 lbs., during 10 hours daily, at the rate of 2 miles an hour; making 20 miles a day; the horse preserving at the same time his health and condition. I adopt Mr W.'s estimate of a horse's effect upon a railway, because it corresponds nearly with the results of observations of my own. On a railway in the West of Scotland, the horses average in weight from 7 to 8 cwt. each; they drag from 7 to 8 tons during 8 hours a-day, at a speed of from 2½ to 3 miles an hour: their weight bears the same ratio to their load as that of Mr Wood's horses; in this respect, then, they are equal to the latter; but otherwise they have rather the advantage in effect; for multiply the speed by the time 2½ × 8 = 20 effect.

or 3 × 8 = 24 ——

Mean = 22 ——

While by Mr W.'s account it is 2 × 10 = 20 ——[*]

---

[*] To exhibit the comparative effects of two horses, I would multiply together the power, speed, and time of working of each horse, and divide the product by his weight. Indeed we may, for the formation

The horses I describe being the property of the persons who drive them, their condition is far inferior to that of English draught horses in general; and the quality of their food is no doubt equally so. It seems generally admitted, indeed, that the Scotch draught horse is a more serviceable animal than the English, in proportion to size and food consumed. At his utmost speed a horse cannot, of course, drag any thing; and the amount of his draught decreases progressively from his lowest rate of motion upwards. Upon the result of his experiment, that a horse works with a power of 112 lbs. at 2 miles an hour, Mr Wood founds the following formula for determining his working power at every rate of speed. He makes $V =$ velocity; 224 lbs. is then the power at 1 mile an hour, and $\frac{224}{V}$ or 224 divided by velocity, the power at any other rate of speed. We have another formula for the same purpose from Professor Leslie, stated thus, $(12-V)^2$, V representing miles an hour; which means substract the number of miles an hour rom 12, and multiply the remainder by itself for the power in lbs. The deductions from each formula are as follow:—

---

of the product to be divided by his weight, include among the factors any number of known circumstances capable of influencing the profitable effect of horses—such as food consumed, durability, &c.

TABLE I.

Speed in miles an hour.	Power by Wood's formula.	Power by Leslie's formula.
1	224	121
2	112	100
3	$74\frac{2}{3}$	81
4	56	64
5	$44\frac{4}{5}$	49
6	$37\frac{1}{3}$	36
7	32	25
8	28	16
9	$24\frac{8}{9}$	9
10	$22\frac{4}{10}$	4
11	$20\frac{4}{11}$	1
12	$18\frac{2}{3}$	0

Of the above results, those from Mr Leslie's formula are generally, perhaps, nearest the truth, if the time of working under each is to be considered the same, and of considerable duration. Yet are they far from strict accuracy, for 12 miles an hour is much under the speed at which most horses could drag nothing; and it is a rate at which no horse could move unloaded during nearly the same time that he could move at the inferior rates of speed, with the corresponding exertions of power.

The deductions from Mr Wood's formula would correspond better perhaps with the results of practice, were the duration of working assumed as diminishing in a certain degree with the increase of speed. To determine the effect of a horse under this consideration, I shall found a rule upon Mr Wood's average, that a horse works with a power of 112 pounds, at 2 miles an hour, during 10 hours, and shall express his time of working (T,) at any other velocity, by 12—V, and, conversely, his velocity for any other duration of time, by 12—T, V being miles an hour, and T, hours a day, so that either T or V being given, the other is found by subtracting the datum from 12.

Now, the effect of an animal's operation being his time of working, his speed, and his power multiplied together, Mr Wood's formula modified by mine becomes either,

$$\frac{12-V\times V\times 224}{V} \text{ or } \frac{12-T\times T\times 224}{V} = T\times V\times P=$$

effect.

The following Table contains the results.

TABLE II.

Time in hours a Day.	Velocity in miles an hour.	Power in lbs.	Effect.
11	1	224	2464
10	2	112	2240
9	3	$74\frac{2}{3}$	2018
8	4	56	1792
7	5	$44\frac{4}{5}$	1564
6	6	$37\frac{1}{3}$	1344
5	7	32	1120
4	8	28	896
3	9	$24\frac{8}{9}$	672
2	10	$22\frac{4}{10}$	448
1	11	$20\frac{4}{11}$	224
—	12	$18\frac{2}{3}$	——

Formulæ are rather apt to make nature bend to their deductions.

The contents of the above Table may approach the truth, but I am far from believing that they reach it: at 3, 4, or 5 miles an hour, good horses will, with loads adjusted to the speed, work longer than at any slower pace with the load corresponding to it; or, if the time of working be made the same, they will drag greater loads in proportion to speed: the effects ought therefore to appear the greatest at or about those velocities. Much, however, will, in this respect, depend on the breed of horses, and on their being, by their form, better calculated for draught or for speed. The horses used for stage coaches in some parts of England are made to run their stages at the rate of 10 miles an hour. Each relay performs its stage, averaging 10 miles, twice over, equal to 20 miles in 2 hours daily. The lightest description of coach, with its average load of passengers, &c. cannot be estimated under 30 cwt.; this gives to each of the 4 horses, 840 lbs. in draught: now, if we assume the friction to be, as is commonly supposed, $\frac{1}{30}$ of the draught, we have each horse's power $=$ 28 lbs. If the friction is $\frac{1}{35}$, as I suppose it on Macadam roads, the power exerted by each horse is $=$ 24 lbs.

Again, the light coaches travel between Glasgow and

Edinburgh in 5 hours, each relay also going twice through its stage; this gives each horse an average of 2½ hours travelling, at a speed of $8\frac{4}{10}$ miles an hour. These results of practice differ little from those of the formula, as will be seen on comparison.

TABLE III.

Comparison of some results of practice with those of the formula $\frac{T \times V \times 224}{V}$.

	Time in hours.	Velocity in miles an hour.	Power in lbs.	Effect.
IN SCOTLAND, Case 1st,	$2\frac{1}{2}$	$8\frac{4}{10}$	24	504
IN SCOTLAND, Case 2d,	$2\frac{1}{2}$	$8\frac{4}{10}$	28	588
By $\frac{12 - T \times T \times 224}{V}$	$2\frac{1}{2}$	$9\frac{1}{2}$	$23\frac{2}{3}$	560
Or by $\frac{12 - V \times V \times 224}{V}$	$3\frac{6}{10}$	$8\frac{4}{10}$	$26\frac{2}{3}$	806
IN ENGLAND, Case 1st,	2	10	28	560
IN ENGLAND, Case 2d,	2	10	24	480
By $\frac{T \times V \times 224}{V}$	2	10	$22\frac{4}{10}$	448

This comparative view shows that the contents of Table II. keep on the side of moderation, which is certainly most desirable, since it is with reference to these that I mean to lay down the effect of the operation under different circumstances, of horses upon railways.

OPERATION OF HORSES UPON RAILWAYS.

The draught of any power (P,) upon a level railway having been determined as = P × 200, it follows that, if the power of a horse under different circumstances be multiplied by that number, the product will exhibit his correspondent amount of draught, as is shown in the subjoined Table, founded upon the contents of Table II.

TABLE IV.

Operation of Horses on a Level Edge Railway.

Time of working in hours a day.	Velocity in miles an hour.	Draught in pounds.
——	1	44800 or 20 Tons.
10	2	22400 or 10 Tons.
9	3	14933·$\dot{3}$
8	4	11200
7	5	8960
6	6	7466·$\dot{6}$
5	7	6400
4	8	5600
3	9	4977·$\dot{7}$
2	10	4480
1	11	4072·$\dot{6}$
——	12	3733·$\dot{3}$

If we contrast, with the contents of this Table, some accounts of the actual performance of horses, we shall see how very moderate are the former. Mr James Jessop, London, saw a horse drag, for a short time, by way of experiment, 27 tons on a level. On Lord Elgin's railway, each horse drags regularly 10 tons, besides waggons, which must be in all 12 tons on a level. On Sir J. Hope of Pinkie's railway, each horse is stated to draw 10½ tons, at 4 miles an hour. This is wonderful; but I myself have seen an active and rather light horse drag about 7 tons at 4 miles an hour on a level, and was told that it was his usual draught and speed during 7 or 8 hours daily; say 15,680 lbs. during 7 or 8 hours, at 4 miles an hour, while, by the Table, we have only 11,200 lbs. during 8 hours, at 4 miles an hour. With the full load for a horse, weighing about 10 cwt. namely, 10 tons, I have seldom witnessed a greater working speed than about 2½ miles an hour. It will thus be seen that the estimate of the average working draught of horses formed upon Mr N. Wood's observations, is, perhaps, as applied to Scotch draught horses at least, rather low than otherwise.

I shall now give some examples of the degree in which the amount of a horse's draught becomes diminished on railways that are more or less inclined; assuming, as before, his draught on a level as 10 tons, at a speed of 2 miles an hour, during 10 hours a day, or assuming his power employed as 112 lbs. and calculating the draught for each elevation by the formula—

$$P \times \frac{200}{1 + (200 \times E.)}$$

TABLE V.

Operation of Horses on Inclined Railways.

Power in Lbs.	Elevation of Plane.	Draught in Tons and Cwts.
112	Level,	10
—	1 in 800	8
—	1 in 400	6 .. $13\frac{1}{3}$
—	1 in 300	6
—	1 in 200	5
—	1 in 190	4 .. $17\frac{1}{3}$
—	1 in 170	4 .. 11
—	1 in 150	4 .. $5\frac{3}{4}$
—	1 in 140	4 .. $2\frac{1}{3}$
—	1 in 130	3 .. $18\frac{3}{4}$
—	1 in 100	3 .. $3\frac{2}{3}$

An instance is quoted in the article " Railways," Supp. Encyc. Brit. of horses dragging each about 15 tons of coals down an inclined plane of 1 in 98, and re-ascending with the empty waggons. Now, of the usual waggons, 15 tons of coals would not require fewer than 11 or 12; the ordinary weight of each is about 7 or 8 cwt.; say 12 × 7 = 84 cwts., or 4 tons, 4 cwt.: the resistance of this amount in draught on an inclined railway of $\frac{1}{98}$ elevation is, friction 47 pounds, + gravity 96 pounds, equal to 143 lbs.; thus each horse, in ascending, overcame a total resistance of 143 lbs. If the horse gave any assistance in the descent, it must have been in checking the gravitating impetuosity of the load, for of 15 tons on a slope of 1 in 98, the gravity is = 363 lbs., from which deduct the friction, = about 176 lbs., and we have 187 lbs. free impulse of gravity; this would make it necessary to have some of the wheels locked, in order to bring the friction more nearly to counterpoise such gravitating impulse.

I may here observe that, as a carriage will be at the point of spontaneously descending an inclined plane, when its friction is to its weight as the height is to the length of the plane—the ordinary carriages on edge railways will be at the point of spontaneous descent on a plane of $\frac{1}{209}$ elevation. To obviate this, and to effect a halt more readily, some railway carriages and the coaches on the Stockton and Darlington railway are furnished with a simple contrivance, called a brake, which, by effecting a pressure on the rims of the wheels, produces any required amount of friction.

We shall now consider the performance of horses when *speed* becomes the principal object in railway communication; as must ever be the case when passengers are to be conveyed. On referring to Table II.

it will be seen that a horse working 2 hours a-day at the rate of 10 miles an hour, can exercise a power of $22\frac{4}{10}$ lbs.; this, multiplied by 200, gives 4480 lbs., or 2 tons as the draught on a level; and that, at 11 miles an hour, his power is $20\frac{4}{11}$ lbs., which, multiplied by 200, gives 1 ton $16\frac{1}{3}$ cwt. on a level. If we suppose his power, as in the case of the English stage coach horses already noticed, to be, at 10 miles an hour, 28 lbs., his draught will be $2\frac{1}{2}$ tons; or, if 24 lbs., his draught will be 2 tons 3 cwt. nearly.

With reference to the conveyance of passengers, I adopt $22\frac{4}{10}$ lbs. as the power of a horse at 10 miles an hour, as by Table II.; and consequently 2 tons as the weight of the coach with passengers, which he is to draw; his stage will be, of course, 10 miles, and will be twice run by him daily—going and returning. 22·4 lbs., then, being his exertion required, and 10 miles an hour his speed on a level, I construct the following Table, to show in what degree that must be increased, and this diminished, when he comes to drag his coach of 2 tons upon certain inclinations of plane. The power required at each degree of elevation is computed by the formula $F + \overline{D \times E}$; and the speed with each exertion of power, by $\frac{224}{P}$ the converse of $\frac{224.}{V}$

TABLE VI.

Performance of horses in light draught on inclined railways.

Draught supposed a coach with passengers in tons.	Elevation of plane.	Power in lbs. required at each degree of elevation.	Speed in miles an hour, compatible with each degree of power employed.
2	Level.	22·4	10
–	1 in 400	33·6	6·$\dot{6}$
–	1 — 300	37·$\dot{3}$	6
–	1 — 200	44·8	5
–	1 — 190	45·97	4·87
–	1 — 180	47·2	4·74
–	1 — 170	48·75	4·59
–	1 — 160	50·4	4·$\dot{4}$
–	1 — 150	52·26	4·28
–	1 — 140	54·4	4·1
–	1 — 130	56·86	3·93
–	1 — 100	67·2	3·$\dot{3}$
–	1 — 50	112	2
–	1 — 22·$\dot{2}$	224	1

At a colliery lately opened in my neighbourhood, where, from the superiority of the coal, a great demand took place before a proper road had been completed, I have repeatedly seen long trains of carts dragged up an ascent of 1 in 10, which is, however, only 50 to 60 yards in length; its surface consisted of a mixture of soft deep clay and large stones, so that the friction upon it will, I am sure, be much underrated when I say it was $\frac{1}{30}$ of the draught: each cart contained 13 cwt. of coals, and say cart = 7 cwt., the draught becomes 1 ton, of which $\frac{1}{10}$ gravity = 224 lbs. + friction $\frac{1}{30}$ or 74·6 lbs., give a whole resistance = 298·6 lbs. to each horse. Yet many of these were of the most wretched description—being the property of the town coal-carriers. The resistance would be just about equal to the above, were a horse to drag a coach of 2 tons up an inclined railway of 1 in 16½, or were he to drag 26⅞ tons upon a level.

A railway coach I have not yet seen, nor have I heard of one that had been built expressly for the purpose. Those on the Stockton and Darlington railway are common heavy stage coaches slightly altered; they contain 6 persons inside, and 16 or more outside, and must weigh, with their complement of passengers, considerably more than two tons. In one of these a friend of mine travelled between Stockton and Darlington, a distance of 12 miles, in 70 minutes; this was at the rate of fully 10¼ miles an hour: the same horse took the coach back again, making thus his daily work 24 miles, or 2 hours 20 minutes, at 10¼ miles an hour. Although the coach had no springs, its motion was more easy than that of a coach with springs on a Macadam road. By this smoothness of movement, tear and wear must of course be diminished, and railway coaches may be proportionally lighter than others; they do not need to be fitted for turning, but may be drawn indifferently by either end; and their wheels may, by having the edges of their flauches made of sufficient breadth, be adapted for running upon a common road or street; this would, however, render springs necessary.

With reference to the last Table, it is to be observed, that when the coach is brought to ascend any inclined plane, the horse, with the corresponding increase of exertion and diminution of speed, becomes employed in a way that admits of a longer continuance of working, and he, in fact, derives a degree of refreshment from the change in his mode of action; nor does this arise merely from the change in his muscular effort by which it is accompanied, it accrues mainly from the circumstance of his being occupied in a less laborious operation.

There are persons, chiefly anatomists, who deny that horses can obtain any degree of "rest" from slight ascents of road; because, they say, every muscle of the body is more or less in operation so long as an animal is in motion. Such argument is, however, little better than a logical quibble. If the term *rest* signifies a total cessation from motion, animals cannot certainly enjoy it so long as they continue to walk; but, if by *rest* is understood any degree of relief from fatigue, animals, though continuing to move, do assuredly obtain it by a shift of their chief muscular strain; and he must have little experience in the use of his own limbs, who is of a contrary opinion.

OF LOCOMOTIVE ENGINES.

Most persons must have had an opportunity of observing, that when a force is applied to the spokes of two opposite wheels of a carriage, sufficient to produce a rotatory motion in those wheels, a progressive motion of the carriage is thereby effected.

Were a force thus employed, unlimited in amount, the load that it could move in the carriage would also be unlimited; but were the increase of load, instead of being placed in the carriage that has the force applied to its wheels, to consist of a separate carriage or train of carriages attached to the former, a limit would forthwith take place to the influence of such power by such means. This limit is, the amount of friction on the ground, of the rims of those wheels that have the force applied to their radii. Were they placed on a surface perfectly smooth and without friction, they would be moved only as if suspended in the air, and could effect no progressive motion, how great soever the power applied to them; but on surfaces such as do exist, wheels may, as above, be exercised against resistances in draught, up to that point at which they begin to slip, or to have their amount of friction overcome.

The friction of a carriage's wheels, when thus used, is termed adhesion; and a precise measure of its amount on any surface is just that force which would drag the carriage *with its wheels locked.* The foregoing enunciation applies strictly to the mode of action of locomotive engines.*

This machine effects its progressive motion by turning its wheels through the means of its crank-rods, which are attached to the radii of the wheels, about one foot distant from their centres, or more or less according to the range of the pistons' strokes. The revolution of the wheels thus produced, accomplishes a progressive motion, by the friction or adhesion of the rims upon the rails. The employment of a wheel, as in L. Es., is closely analogous to that of an animal's limb in walking; both act as levers of the second class, in which the resistance is placed between the power and the prop, as illustrated in the comparative figures 1, 2, and 3: in each of these a weight (*r*) suspended by a cord over a pully, is made to point out the direction in which the resistance bears; and, in each figure, P shows the point of application of the power, R that of the resistance, being in the animal the articulation of the joint, and in the L. E. the axle of the travelling wheel; and F shows the fulcrum of the lever upon the ground. M points out in the animal member a portion of the muscle, and in that of the L. E., a portion of the crank-rod; these being the instruments through which respectively the power is applied. *r*, applied at R, consists, in the L. E., of the weight of the machine, the friction of its moving parts, and of any draught it may have attached to it; and, in the animal likewise, *r* consists of the friction of his moving parts, and the weight of his body, with the resistance of any load that he may have to carry, or drag, or push.

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* I shall henceforth express Locomotive Engine by its initial letters L. E.

The effective force of the L. E., applied through the crank-rod, varies much (as does that of the animal applied by his muscles) with the changes in position that take place in the course of the radial motion; that of the L. E. has, however, a great advantage in this—that there are only two points in the course of each revolution of the wheel, at which it becomes absolutely nugatory—namely, when the point of application of the crank-rod is directly above the centre of the wheel, and when it is directly below it. The wheel, as above employed, is to be viewed as a continuous system of levers; and each point of its circumference, as it is applied in succession to the rail, as the point of rest of another lever of the system advanced forwards to be exercised against the resistance. I shall again have occasion to notice this principle, when I come to treat of the velocity of L. Es.

The dragging power of a L. E. is to be considered as limited solely by the amount of adhesion of its wheels upon the rails; the steam power being of course unlimited, save by the strength of materials and construction of the engine, and by the quantity of fuel supplied. We should expect that this adhesion, and consequent dragging power, would be determined by finding the amount of force required to drag the L. E. with its wheels locked, or a block of iron of similar weight, upon a level rail. The friction of iron sliding upon iron, has been determined by Coulomb to be from $\frac{1}{5\cdot6}$ to $\frac{1}{6\cdot4}$ of the weight, according to the less or greater polish of the surfaces by rubbing; say $\frac{1}{6}$; then we should be entitled to expect that, on an inclined rail of about 1 in 7·2, which elevation makes allowance for the diminution in adhesion necessarily arising from the inclination of plane—a L. E. would stand still if its wheels were locked, or if its steam power operated merely to prevent its wheels from revolving downwards: Secondly, that it would ascend such plane if its steam power were so increased as to cause its wheels to revolve in any degree upwards: Thirdly, that it might carry in its ascent a load, *bearing upon its own wheels*, limited only by its extent of steam power and strength of materials: Fourthly, that it might, while unattached to any other vehicle, acquire a speed in its ascent limited solely by its compass of steam power, and velocity of piston, and by the friction of its moving parts: Lastly, that, at every inferior degree of elevation, the L. E. would operate similarly upon a load contained in separate carriages, which, in conjunction with its own weight, would form a resistance equal to that of itself singly upon the plane of 1 in 7·2. Such a proportion of adhesion, however, with its results, has not been found to obtain in practice. According to the experiments of Mr N. Wood, who has had upwards of 10 years experience of L. Es., the amount of adhesion in the most favourable weather, when the rails are either quite dry or completely wet, is only appreciable as $\frac{1}{9{\cdot}25}$ of the weight of a L. E. This defalcation Mr Wood ascribes to "the force of steam at different periods of the strokes being irregular upon each wheel." The weight of a L. E. being about 16,800 lbs. $\frac{1}{9{\cdot}25}$ of this gives the adhesion = 1816 lbs. which multiplied by 200, the mechanical advantage on a railway, gives 363,200 lbs. or 162 tons as the draught upon a level, under the most advantageous circumstances. On the other hand, when a railway is in the worst possible state, namely, when covered with viscid mud, as happens in drizzly weather, which acts like grease or any other unctuous matter in diminishing friction, the adhesion becomes so far reduced as $\frac{1}{21\cdot62}$ of the L. E's. weight, equal to 777 lbs. which multiplied by 200, gives 70 tons only as the draught of carriages on a level. Mr Wood states, that with a load of 70 tons in the worst state of the rails, the L. E.'s wheels still slipped in a slight degree, although the usual speed was maintained by an increased velocity of piston and rotation of wheel. As this slipping is injurious both to the rails and the wheels, he recommends the adhesion and power of L. Es. to be estimated for security against the worst circumstances at $\frac{1}{25}$ only. We have thus the L. E.'s weight 16,800 lbs. divided by $25 = 672$, which multiplied by 200, gives 60 tons as the draught of carriages on a level under the worst circumstances. And universally, whatever is the weight of a L. E. and whatever is its adhesion, we have $L\,E \times a = P$; L E representing the weight of the L. E., a its adhesion in fractions of its weight, and P its power on a level; and $\overline{L\,E \times a} \times 200 = D$, the draught on a level railway. It is here to be observed, however, that P is by no means to be considered as the absolute amount of the L. E.'s power, but only as that extent in which it can be exercised consistently with the amount of adhesion, and beyond which its effect would only be to make the wheels slip round without an adequate progressive motion. With this reservation only, is L E × a to be taken as equivalent to P.

OPERATION OF LOCOMOTIVE ENGINES ON INCLINED RAILWAYS.

On an inclined plane the gravity of the L. E. itself comes to act as a resistance against its operation in ascending: and when the L. E. is upon a plane, whose height bears the same ratio to its length that the adhesion of the L. E. bears to its weight, its intrinsic resistance and power are to be considered in equilibrio, and the L. E. consequently incapable of dragging up any thing besides itself. On a plane of any inferior degree of elevation it will drag up an extraneous load, the resistance of which, together with that of its own gravitating tendency, must form a gross resistance not exceeding L E × a; and the whole resistance to an L. E.'s power, on a plane of any elevation, will be =

$$\overline{LE \times E} + \overline{D \times E} + \overline{D \times F} = R$$

L E representing the weight of the L. E., D that of the draught, E the elevation of plane in fractions of its length, F the friction of the draught in fractions of its weight, and R the whole resistance. In R the resistance of the moving parts of the L. E. might be included, but it is a quantity that varies only with the velocity of pistons; it was found by Mr N. Wood to be, at upwards of five miles an hour, equal to 213 lbs.; this amount will increase and diminish with the velocity, but not in precisely the same ratio. In order to find the nett power of a L. E. on an inclined plane, or that portion which is over and above what is requisite to counterbalance its own resistance of gravity, and which consequently remains applicable to a certain draught of carriages, we have only to subtract the gravity of the L. E. on the plane, from its amount of adhesion or power on a level, thus,

$\overline{\text{L E} \times a} - \overline{\text{L E} \times \text{E}} = \text{P} =$ nett power sought.

P being found, we have, by a similar formula to that used in horse power,

$\text{P} \times \frac{\text{M A}}{1 + (\text{M A} \times \text{E})} = \text{D Q}$ the draught of carriages sought on the given inclination of plane; and on a railway, $\text{P} \times \frac{200}{1 + (200 \times \text{E})} = \text{D Q}$

The annexed Table contains the nett power consistent with the adhesion and the draught at various elevations of plane of a L. E. weighing 16,800 lbs., and having travelling wheels of 4 feet in diameter. In my calculations I have assumed the adhesion at $\frac{1}{21\cdot62}$ of the L. E.'s weight, giving a power of 777 lbs., as exhibited by the L. E. according to Mr Wood's experiments, in the worst state of the rails: I consider this estimate sufficiently low; because inclined planes must form but a small proportion of any extensive railway; and because, moreover, the same unguent which diminishes the adhesion, must also, in a great measure, prevent the tear and wear that might otherwise arise from the slipping before alluded to. The contents of the Table, then, are to be considered as representing, respectively, the operation of a L. E. weighing 16,800 lbs., under the worst circumstances.

Operation of L. Es. on Inclined Railways.

Elevation of plane.	*Nett power in lbs. consistent with adhesion, at each degree of elevation.	Nett draught in tons and cwts.
1 in 400	735	43 .. 15
1 — 300	721	38 .. 12½
1 — 200	693	30 .. 18½
1 — 150	665	25 .. 9
1 — 120	637	21 .. 6½
1 — 100	609	18 .. 2½
1 — 80	567	14 .. 8⅔
1 — 50	441	7 .. 17½
1 — 30	217	2 .. 10½
1 — 21·62	——	————

In corroboration of what is above laid down, we have, on the Killingworth railway, in the best state of the rails, a L. E. weighing 16,800 lbs., dragging 51 tons, 18 cwt. up an inclined plane of 1 in 104·2; thus exhibiting a power and adhesion of wheel equal to 1810 lbs., which would, on a level, allow a draught of 161 tons. On the same railway we have 48 and 50 tons taken up an ascent of 1 in 330; and with the latter loads we have an average speed in the journey of 4·9 miles or 6·6 miles an hour, as the travelling wheels of the L. E. are 3 feet or 4 feet in diameter. On the Stockton and Darlington railway the L. Es. travel, I have been told, 20 miles in 4 hours, with from 70 to 90 tons in draught.

SPEED OF LOCOMOTIVE ENGINES.

From the extravagant ideas that were at first entertained and promulgated, by some persons, concerning the speed of travelling likely to be attained through the employment of L. Es., much discredit has fallen upon these machines. Their power was viewed as constant and undiminishing, like the gravitating force of a body descending towards the earth; and consequently, from being applied to a resistance consisting of the friction of carriages, which is equal in equal times, as capable of an acceleration of velocity unlimited, save by the resistance of the atmosphere. In such speculations the nature of this machine, or indeed of any machine, must never have been considered. The power of a machine diminishes with the velocity, in precisely the same manner as that of an animal; the only difference is in degree. The former has indeed this great advantage, that it is not susceptible of fatigue, and that the materials, which furnish its power, may perhaps be continued or augmented at our will.

An increased speed of revolution of a L. E.'s travelling wheels, while these are of a given size and construction, can be produced only by an increased velocity of its pistons: but, by the law of pneumatics, the greater the velocity of the pistons, the less must be the intensity of the impress of steam on them, while this is at a given density and rate of production; hence it follows that, if a L. E. were even altogether unloaded, its velocity would be limited to that degree at which the resistance of its moving parts, transmitted to its pistons, and the pressure of steam upon these would approach an equilibrium: when the case of the machine would precisely resemble that of an animal at his greatest speed, when he expends his whole force in carrying his body forwards, and is unable to drag any load: and if by any mysterious power, the speed of the L. E. were accelerated, so that its pistons should attain a velocity equal to that with which the steam might tend to rush through the throttle valve; then would the steam apply no pressure whatever to the pistons; any more than would a horse's limbs to his body, if he were drawn along at a velocity equal to that of the impulses of his limbs. The progressive motion of an animal is effected by the impulses of his limbs against the ground; the velocity and intensity of his crural action, are limited, like those of the L. E.'s pistons, to that point at which his vital force, and the resistance from his moving parts and bodily weight approach an equilibrium: and his speed of progressive motion is limited by that of his crural strokes, just as the speed of travelling of a L. E. is limited by the velocity of its piston strokes: and, in both the animal and the machine, the more near is the advance to this terminal velocity, the less must be the extraneous load conveyed.

The speed of a L. E., then, while its wheels, and its load drawn remain the same, can be increased beyond a certain extent, only by an increased force of steam, by an enlargement of the communication between the boiler and cylinders, and by an increase of the supply of fuel; which means are evidently limited.

It is practicable, however, to give a great command of speed to L. Es.; and to do so with a very trifling addition of power or diminution of load; because it is accomplished without an increased velocity of pistons: and on this chiefly is founded the superiority of these machines over every description of animal agent.

One method of obtaining this command of speed, consists simply in applying to a L. E., travelling wheels of greater dimensions.

Mr N. Wood has the merit of having been the first person to conceive that any advantage might be derived from increasing the size of a L. E.'s wheels: and he found on making the experiment that, with wheels of 4 feet diameter, a L. E. travelled 48 miles in the same time that, with wheels of 3 feet diameter, it had occupied in travelling 36 miles; or that the increase of speed was in the ratio of the increase of the wheels, having been from 4·95 to 6·6 miles an hour; while the load drawn and the fuel consumed were in both cases the same: he found also that, when the speed of travelling and the fuel consumed were the same, the draught might be increased; and speed and draught being the same, that the fuel might be diminished nearly in the ratio of the increase of wheel. The cause he assigns for the two latter results is diminution of friction in the working parts of the engine. Now the resistance, from this cause, he ascertained to be equal to 213 lbs., when the speed of travelling was about 5⅛ miles an hour, and supposing it to be diminished even in exact proportion to the diminution of velocity in the rubbing parts of the engine (which, however, I have reason to doubt,) this would amount, in any case, to only a trifling quantity. The greater power, exhibited by the engine with 4 feet wheels, must, I conceive, have been mainly owing to the increased density and consequent force of steam arising from the diminished velocity of the pistons, while the rate of production of steam and the speed of travelling remained the same. With the change from 3 to 4 feet wheels, Mr W. discovered no increase of resistance, and he did not suspect that there was any. This was, however, an error; for the resistance of the draught, which is transmitted through the travelling wheels to the pistons, is increased with the enlargement of these wheels. The resistance is increased also in as far as concerns the rolling of the wheels themselves on the rail; but this is quite insignificant unless their size be beyond what would for other reasons be admissible. Mr W.'s not having perceived any increase of resistance in the first experiment above quoted, may have arisen from the L. E.'s being considerably underloaded, the draught conveyed in each journey having been only 36 tons 11¼ cwt.: for, as almost the whole increase of resistance with larger wheels is derived from the draught, it must necessarily form a less and less proportion of the *whole resistance* as the draught is diminished: and, if there were no draught at all, the larger wheels would afford advantage with scarcely any abatement, except from that trifling quantity produced by their rolling upon the rails.

Now of 36 tons 11¼ cwt. in draught, the resistance is, on a level, 409½ lbs.; the resistance of the moving parts of the engine is, as above, 213 lbs. (which is unchanged, because the velocity of piston is here the same;) making a total resistance opposed to the steam power equal to 622·5 lbs.: and the increase of the draught's resistance by enlarging the wheels from 3 to 4 feet in diameter, is, as I shall presently explain, equal to $\frac{1}{9}$ of the 409½ lbs.; which of 622½ lbs. forms only about a $\frac{1}{13\cdot6}$. This might be compensated by a slight difference in the state of the rails, the quality of the coal, &c. as will be readily conceived when it is remembered that the influence of the state of the rails reaches sometimes to no less an amount than $\frac{1}{3}$ of the draught. Mr W. did, however, perceive to what an extraordinary conclusion it would lead, to suppose that all was gained and nothing lost by the enlargement of wheels: he therefore endeavoured to discover some source of increasing resistance; but in this he failed. In order to make it out he multiplied together the *resistance* of the engine's moving parts, and the *space* moved over by the draught, with different sizes of wheels; and the products, thus obtained, he assumed as representing the comparative resistances overcome: and, as he conceived the resistance of the engine's moving parts, diminished by the increase of the wheels from 3 to 4 feet; to be diminished in a less degree as the wheels should exceed this; he had, consequently, for the formation of his product at every increase of wheel, two factors, one of which had become less; namely, that which expressed the diminution of the L. E.'s esoteric resistance, while the other had become greater; namely, the space through which, in a given time, the load was drawn: and, as he supposed the latter to have increased in a greater ratio than that in which the former had diminished with each increase of wheel, he had thus a greater product to express the resistance overcome.

Now, an increase in the space described in a given time cannot be viewed as indicative of a greater resistance overcome, or of a greater power expended, unless it is attended and produced by an increased velocity of the power; but it is the peculiar property of larger travelling wheels, that they effect an increase in the speed of a L. E. without an increased velocity of the pistons and of the efflux of steam; and the resistance of the draught of carriages cannot be increased, merely by the greater speed attained through the larger travelling wheels, for it remains, by the law of friction, equal in equal times, without respect to the space through which the draught is moved. The increase of the draught's resistance, that accompanies an enlargement of the travelling wheels, is founded on the principle of action of L. Es. stated by me at the commencement of the subject. The point Z, (Fig. 4,) at which the circumference of the wheel meets the ground, it will be remembered, is to be considered as the rest of a lever; the axle R is the point between the rest and the power, at which the resistance of the draught is applied; and the application of the power is at P, that part of the radius of the wheel to which the lower end of the crank-rod is attached. The power is, as before observed, applied with various degrees of advantage in the different situations occupied by the end of the crank-rod in the course of each revolution; it alternately changes its form of operation too, from that of dragging, to that of pushing; the former taking place when it is in advance of the axle, as at any of the positions A, B, or C; and the latter, when it is behind the axle, as at D, E, or F. But, in every situation, its force is through the cohesion and unity of the parts of the wheel, applied at the point P, which is vertical to the axle and the fulcrum upon the ground; and the advantage of the power, in one respect, depends on the angle that its line of application forms with the lever P O Z. For example,—its effect is less when the lines of its application are represented by P B and P E, than when by P A and

P D, and less when by P C and P F than when by P B and P E; and at O the power has no effect at all.

This disadvantage inseparably attends the production of rotary motion by rectilinear impulse. In L. Es., however, it has been contrived, that when the power is, in one wheel, approaching the least effective line of application, it is, in another, approaching the reverse. In animals, the mechanical disadvantage is far beyond that in the case of L. Es. In those the leverages are so small, and the angles of application of the muscular force so acute, that they have been by some estimated to effect an amount of power equal only to about $\frac{1}{18}$ of the actual force exerted.

It will now be a very simple matter to explain in what manner the resistance of the load, drawn by a L. E., becomes augmented by the application of larger wheels.

The power being applied at P, (Fig. 4,) and the resistance of the draught at R, upon the lever P R Z, the leverage of the power is, consequently, to that of the draught as P Z to R Z. Now, in the L. Es. herein alluded to, the attachment of the crank-rod is about one foot from the centre of the wheel; and this distance cannot be altered while the pistons and cylinders remain the same. P and R, then, are always one foot asunder; and in wheels of 3 feet diameter, the distance of P from Z being $2\frac{1}{2}$ feet, and that of R from Z being $1\frac{1}{2}$ foot, the leverage of the power is to that of the draught as $2\frac{1}{2}$ to $1\frac{1}{2}$; but it is plain, that if we lengthen the lever P R Z, and thereby remove the fulcrum to a greater distance from P and R, P Z must have to R Z a less ratio than it had before: thus, if we apply 4 feet wheels, P Z becomes to R Z only as 3 to 2; that is, the leverage of the draught is $\frac{2}{3} = \frac{10}{15}$ of the leverage of the power; and with 3 feet wheels, the leverage of the former was $\frac{1\frac{1}{2}}{2\frac{1}{2}} = \frac{3}{5} = \frac{9}{15}$ of that of the latter; consequently, the resistance of the draught is, by substituting 4 feet wheels for 3 feet ones, increased in the ratio of 10 to 9. To make up for this, the draught must be reduced by $\frac{1}{10}$ of its amount, or the steam power must be increased by $\frac{1}{9}$ of that portion which is called for by the resistance of the draught; but as the resistance of the working parts of the L. E. is, as before noticed, about 218 lbs. the increase of steam power will be considerably under $\frac{1}{9}$ of the whole; it will therefore plainly be most advantageous to add to the force of steam, instead of reducing the draught, in compensation for the loss of leverage with the larger wheels.

In exemplifying the application of the principle above laid down, I shall take as a standard the performance of a L. E. exhibited on the Killingworth railway, in presence of several engineers. The weight of the L. E. was 16,800 lbs., the diameter of wheels was 4 feet, the speed of travelling averaged 6·6 miles an hour, the draught conveyed was 50¼ tons, including the convoy carriage of 1½ ton—say 50 tons; and the railway was slightly undulating to a rise at one place of 1 in 330. I shall suppose now, that in order to obtain a speed of 8¼ miles an hour, we apply to a L. E., wheels of 5 feet diameter; then we have P Z = 3½ feet, and R Z = 2½ feet; consequently the leverage of the draught $= \frac{2\frac{1}{2}}{3\frac{1}{2}} = \frac{5}{7} = \frac{15}{21}$ of the leverage of the power: but with 4 feet wheels, the leverage of the draught was $\frac{2}{3} = \frac{14}{21}$ of that of the power; thus the resistance of the draught, with 5 feet wheels, is to that with 4 feet wheels, as 15 to 14; the draught of 50 tons must, to be adjusted to this, be reduced to 46⅔ tons—or if the 50 tons remain undiminished, we must augment the steam power applicable to the draught, in the proportion of 15 to 14: the resistance of 50 tons in draught is = 560 lbs. that of the moving parts of the L. E. = 213 lbs. making in all 773 lbs., and $\frac{1}{14}$ of 560 lbs. = 40 lbs. which is of 773 the $\frac{1}{19\cdot325}$ part; we have therefore, instead of reducing the draught by $\frac{1}{15}$, to increase the force of steam by only the $\frac{1}{19\cdot325}$ of its whole amount, in order to adjust it to the increased leverage of the draught, and then we have the 50 tons conveyed at the rate of 8¼ miles an hour. According to Mr Wood's supposition, for he never had applied wheels of greater diameter than 4 feet, the reduction of the draught, or the increase of steam power, would have to amount to above $\frac{1}{8}$, in substituting 5 feet wheels for 4 feet ones.

It is wonderful that he did not suspect some inconsistency to be involved in the proposition, that in the increase of wheel from 3 to 4 feet, there should be no increase of resistance, while in that from 4 to 5 feet there should be an increase equal to $\frac{1}{8}$.

I shall now suppose that we apply to the L. E. wheels of 7 feet diameter, which would produce a rate of travelling equal to 11·55—say $11\frac{1}{2}$ miles an hour; the leverage of the draught will then be to that of the power as $3\frac{1}{2}$ to $4\frac{1}{2}$, or as 7 to 9; that is, $\frac{7}{9} = \frac{21}{27}$ of the leverage of the power; but with 4 feet wheels, the former was of the latter, $\frac{2}{3} = \frac{18}{27}$: by a change then, from 4 feet wheels to 7 feet ones, the resistance of the draught is increased in the ratio of 21 to 18, or of 7 to 6; the 50 tons must thus become $50 \times \frac{6}{7} = 42\frac{6}{7}$ tons; or, the 50 tons remaining, the steam power or fuel must be increased by nearly $\frac{1}{8\cdot33}$ of its whole amount. When we arrive at such a speed as the above, the resistance of the atmosphere comes to be of some importance, and might possibly amount to a further difference in the draught of about $2\frac{1}{2}$ tons.

By Dr Robinson's rule for finding the resistance of the air to a moving body—namely, to multiply the velocity in feet a second by 16, we have the resistance to a square foot of plain surface at one mile an hour, equal to $34{\cdot}41\dot{7}$ troy grains; and, as this resistance increases in about the ratio of the square of the velocity, we have $34{\cdot}41\dot{7} \times V^2$, V being miles an hour, as the resistance in grains to a square foot at any higher rate of speed; which, at 11½ miles an hour, becomes $34{\cdot}41\dot{7} \times 11{\cdot}5^2 = 4551{\cdot}75\dot{1}$ troy grains $=$ ·65 lbs. avoirdupois nearly to each square foot of *flat* surface; but, on such forms of surface as may exist, we shall perhaps come near to the truth if we assume one-half pound avoirdupois as the resistance per square foot of a transverse section of the L. E. where its dimension is the greatest; we should then probably have 10 to 15 lbs. of resistance from the atmosphere opposed to the L. E. when travelling at the rate of 11½ miles an hour. Now the resistance upon the carriage or carriages drawn would not be equal to as much more, for they are in similar circumstances to that of a vessel towed in the wake of another, which, every one must have observed, is done with a slack rope; and the reason is, that the towed or dragged body moves in a fluid already broken into an eddy, and moving also at a certain rate in the same direction with itself. Let us, however, take the resistance upon the draught as equal to that upon the L. E. itself, and we have the whole resistance of the atmosphere, at 11½ miles an hour, equal to from 20 to 30 lbs., which is not far short of from 2 to 3 tons in draught. If, then, the whole increase of resistance, derived both from the increased leverage of the draught and from the resistance of the atmosphere, were to be compensated by reducing the load drawn, we should still have 40 tons conveyed at 11½ miles an hour, being $\frac{4}{5}$ of the draught at 6·6 miles an hour; or if the whole 50 tons were retained, the force of steam, or supply of fuel would require an increase equal to the $\frac{1}{6\cdot49}$ part nearly of its whole amount. There are some inconveniences attending a great size of wheels; in the first place, there is a greater leverage to twist or break the axles; of this, however, from the smoothness of movement on a railway, there must be but little danger: secondly, an increased resistance to the rolling of the wheels themselves upon the rails; but this, within any extent otherwise desirable, would be trifling, and would scarcely be felt but at the outset; and when in motion they would act as fly wheels, and aid in producing regularity of movement: thirdly, large wheels would, on the occurrence of any obstacle, more readily roll off the rails; this again might be obviated by having the rails so elevated above the surface of the ground, as to admit of a greater depth of the flauches of the wheels.

There is, however, a method of increasing the speed of L. Es., without increasing the velocity of the pistons, which will not be attended with any of the above disadvantages, such as they are, because it is not accomplished by means of enlarging the wheels. This method consists in causing the crank-rods to operate through toothed wheels, so as to produce a greater number of revolutions of the travelling wheels in proportion to the number of piston strokes. If we apply to a travelling wheel, and to its crank-rod, sun and planet wheels, that will produce, say two revolutions of the travelling wheel for each double piston-stroke, then we shall have, with 3 feet wheels, a speed of 9·9 miles an hour, instead of 4·95 miles as before; and, with 4 feet wheels, we shall have a speed of 13·2 instead of 6·6 miles an hour.

In this case the resistance of the draught becomes increased on precisely the same principle as in the case of enlarged wheels; and this increase of resistance will, at 13·2 miles an hour, be in the ratio of 6 to 5 over what it was with the crank-rod applied in the ordinary way to the 4 feet wheels; for the lower end of the crank-rod can still only range from 1 foot above to 1 foot below the centre of the travelling wheel; the diameter of the sun and planet wheels must be therefore only 1 foot in each; and the point of application of the power through the crank-rod consequently just 6 inches distant from the centre of the travelling wheel, instead of 1 foot, as formerly; hence R Z (Fig. 4,) now becomes $\frac{4}{5} = \frac{24}{30}$ of P Z; but before we had, with 4 feet wheels, R Z equal only to $\frac{2}{3} = \frac{20}{30}$ of P Z. The increase of the draught's leverage is thus as 24 to 20, or as 6 to 5, as above stated.

I have now to notice a disadvantage that is common to both of the foregoing methods of acquiring command of speed in L. Es. It occurs on their coming to ascend inclined planes; for, on these the whole resistance of gravity will also operate through an increased leverage.

The resistance on an inclined plane, it will be remembered, consists, exclusive of that of the L. E.'s working parts, of the gravitating force of the L. E., and that of the draught, together with the friction of the latter. Now, when this whole resistance (R,) has its relative leverage increased by its $\frac{1}{6}$ part; for instance,—we have, taking 50 tons, as before, drawn with 4 feet wheels up an ascent of 1 in 330,

$$\begin{array}{rcl} L\,E \times \frac{1}{330} & = & 51 \text{ lbs.} \\ D \times \frac{1}{330} & = & 339{\cdot}4 \\ D \times \frac{1}{200} & = & 560 \\ \hline & & 950{\cdot}4 = R \end{array}$$

to which add $R \times \frac{1}{6} = 158{\cdot}4$

then we have 1108·8 lbs. = the resistance with the above increase of leverage. We have now to consider whether the L. E. is capable of overcoming an extraneous resistance of 1108·8 lbs. It was found that, when the adhesion did admit of it, the L. E.'s power overcame a resistance besides that of its working parts, equal to 1810 lbs.; but the adhesion is not affected by an increase of the relative leverage of the resistance, therefore the L. E. can still drag the 50 tons up the inclined plane of 1 in 330; and the addition to its force of steam requisite for this purpose, will amount to $\frac{1}{7 \cdot 84}$ of the whole. If L., then, represent the increased leverage of R, in decimals of its former amount, the resistance on any inclined plane, with any increased leverage of R, will be $= R + \overline{R \times L}$; and while this amount shall not exceed 1810 lbs., we have practical certainty that it will be within the compass of the steam power.

From the foregoing observations it will be seen that, though the amount of draught conveyed by a L. E. must in all cases be regulated by the degree of elevation of any inclined planes which it may have to ascend in the course of its journey, yet, that as this regulation has reference only to the adhesion of the wheels, which has to be estimated so low as to provide against the worst state of the rails, no additional allowance can ever have to be made from the draught on account of its increase of leverage; for the greater leverage of the draught does not, as I have said, in any degree affect the adhesion of the wheels, it operates solely against the force of steam, which must always be fully adequate to counterbalance it, when the draught has been adjusted to such low estimate of the adhesion. In proof of this, let us take the table of performance of a L. E. on inclined railways; the contents are calculated, it will be remembered, from an adhesion equal to L E $\times \frac{1}{21{\cdot}62}$, being that under the most unfavourable circumstances; and at every elevation of plane, the gross resistance R, of the gravity of the L. E. and the draught, and of the friction of the draught, amounts to 777 lbs., to this add R $\times \frac{1}{5} = 155{\cdot}4$, the additional resistance caused by the adoption of the sun and planet wheels, as before specified, and we have at each elevation of plane, with the draught opposite to it in the table $777 + 155{\cdot}4 = 932{\cdot}4$, which is little more than one-half of 1810 lbs., the greatest extraneous resistance that was found to be overcome by the steam power, when the adhesion did admit of it.

I shall now make a comparison between the effect of the operation of L. Es. and of horses; and for this purpose I shall assume the speed of the L. E. as only 10 miles an hour; I shall suppose likewise that there are one or more inclined planes of $\frac{1}{200}$ elevation in the course of its journey of, say 40 miles. I shall assume a draught also adjusted, as in the Table, to the worst state of the rails, which is thus 30 tons: we have then the journey of 40 miles performed in 4 hours, and the same back again, making 80 miles in 8 hours. With four horses we have a railway coach of 2 tons drawn also through 80 miles in 8 hours: but the draught of the horses is equal only to $\frac{1}{15}$ of that of the L. E.: the performance of the latter is consequently equal to that of 60 horses on a railway. If the greatest inclination of plane in the line of railway cannot be less than 1 in 120, the draught of the L. E. being, by the Table, 21 tons 6½ cwt., say 20 tons, its performance will be equal to that of 40 horses on a railway: nor is the full amount of the superiority of the L. E. yet stated; for while the 40 or 60 horses would, after having, as above, completed their day's work, be obliged to receive that refreshment required for enabling them to undertake as much on the following day; the L. E. would be capable of continuing its performance: it might convey passengers during the whole day, and coals or other goods during the night. I make no account of the increased difficulty that a horse will experience from carrying his own body up an ascent, because, on no railway, can this ever be worthy of notice. It does not seem necessary to embrace, in this comparison, the performance of horses on common roads or on canals. With respect to the latter, I shall only mention that, at a speed of 2 miles an hour, a horse has been found to drag 30 tons on a canal; this shows a performance three times as great as that of a horse at the same speed on a railway; but any degree of advantage continues only till the speed reaches about 3½ miles an hour; for, the increase of resistance to a body moving on water being as the square of its velocity, the draught of a horse on a canal becomes at 3½ miles an hour no greater than on a railway. I am inclined to think, indeed, that the resistance on a canal must increase with the velocity in a considerably greater ratio than that indicated by the hydrodynamic law: because the water, when confined between the banks of a narrow channel, must rise to a much greater height on the bow of a boat, than it would do in an open sea or lake.

With regard to the expense of a L. E., we must always have a change with that in the value of coals in different places. Mr Wood states that, as an average of many situations, it may be considered as equal to the expense of 3 horses; this, I have no doubt, is substantially correct: I have been informed that £350 is about the annual cost of a L. E. of the greatest power hitherto used, making allowance for interest and wear. The annual cost of three horses, when we take into account their very inferior durability, and their being liable to many diseases and to sudden death, especially when employed in rapid travelling, may not differ much from the above: it must have no place in such comparative estimates, that those who are skilled in horse-dealing can manage to save themselves from some losses; for the loss must always fall upon some body, and the most experienced may in their turn be imposed on. The coals consumed by the L. E. with 4 feet wheels, in conveying 50¼ tons, as before quoted, through a journey of about 11⅜ miles, amounted to 587 lbs.; or to 51·55 lbs. a mile. The fuel required in a journey may depend in some degree on the number and elevation of the inclined planes; but on these, as they must form only a minute proportion of any railway, the L. E. can, by diminishing its speed, and consequently its velocity of pistons, obtain a greater density and force of steam, while the rate of production of steam remains the same.

We have thus in L. Es., one instance more of the great command of power that is acquired through the agency of steam; and of the superiority of machines when brought into comparison with animals. Although L. Es. have, in several parts of England, been rendered very serviceable, and brought to a considerable degree of excellence; they have yet been scarcely used but in private undertakings, and on a limited scale. They must therefore be considered as being little beyond their infancy; and the public advantages that will one day be derived from them, as probably greater than have yet been conceived. They are chiefly defective with respect to their performance on inclined planes: it occurs to me, however, that, by having the flauches of their wheels toothed, and by applying a rack-work on inclined planes, below the surfaces and at the inner sides of the main rails, the adhesion of their wheels on inclined planes could be brought up to the full amount of their steam power. The resistance that L. Es. could overcome on inclined planes, besides that of their working parts, would thus be raised from 932·4 lbs. to 1810 lbs.; and the load drawn might consequently be at least double of that shown at each elevation, in the Table; for the whole addition of resistance might be formed by additional draught. At all inclinations of plane, indeed, under about 1 in 200, the draught would come to be regulated by the adhesion upon a level.

I have now, I believe, sufficiently explained the operation of horses and of locomotive engines on railways; together with the modifications in their performance, under different circumstances of elevation, load, and speed. With regard to the opinion which I have put forth concerning locomotive engines, it will doubtless be, by some, regarded as extravagant. But I can only say that I advanced towards it with the utmost caution, carefully searching for any inconsistency; and that I have found it to be a necessary consequence of the principles of action that I have developed in these machines. It has become a sort of proverb among unthinking persons, that "what does very well in theory, may not do in practice." Now, when theory and experiment are not found fully to correspond, one of two things must be the case; either, first, that, in the theory, all the circumstances of the subject have not been known and provided for; which just proves that the theory is not the theory of the matter at all: or, secondly, that experiment has not reached to the full extent that the theory did contemplate. The latter, I am surely entitled to say, is the state of the case in question. Indeed, in as far as experiments on locomotive engines have been carried, the results would appear to have rather exceeded, than otherwise, what the theory holds out.

I would not have it to be supposed, moreover, that I look upon the extent of power and speed, which I have taken into my calculations, as the utmost limit to these. I conceive that the scale of operation of locomotive steam engines can only be limited by the amount of population, and degree of productiveness of the district in which they are to become the instruments of commercial and general intercourse; and I must say, that I look forward with confidence to a time when these machines will, in such districts, have supplanted, in a great measure, the agency of animals in all the great purposes of communication.*

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* We hear that experiments are being made relative to the employment of steam carriages on common roads. If these experiments should prove successful, as I have no doubt that they will, we shall find animal power give place to steam power even on common roads. By this application of locomotive engines, it occurs to me that a considerable saving may come to be attained in the construction of railways. The burden-carriages on a railway may be light and numerous, instead of heavy and few; or, if heavy, they may have their weight distributed over any number of points of a railway, by a greater number of wheels—thus the strength and quantity of metal in rails is at present regulated by the weight of the locomotive engines used upon them: but if these shall be found to operate equally well with their travelling wheels applied on the stone part of a railway, the rails may then be adapted for only the light pressure of the carriages in draught. When a locomotive engine is thus employed, it may, for the purpose of lessening the injury to the road, require to have the rims of its travelling wheels made of great breadth; for this would, from distributing the bearing of its weight over a greater surface, diminish proportionally the adhesion and consequent wear at each point of contact on the road.

APPENDIX.

APPENDIX.

IN the experiments on friction of wheel-carriages, I used one of those small carriages that are employed at collieries in conveying the buckets of coals from the mouth of the pit to the coal-heap. It was of nice construction; and the axles and wheels, which were of iron, were very justly fitted to each other. The plane on which I placed it was the roof of an office house, of the description that is covered with pitch and large sand, or very minute gravel; this was well adapted for the purpose, for though not so smooth as a railway, it presented a uniform surface—it had a slight inclination just sufficient for letting off rain water, and against this slope I made the carriage always run. At the upper side of the slope I placed a ladder perpendicularly against the wall of the house, and divided and marked it off into equal spaces of one foot. I had a large pulley set out from the roof of the house between the limbs of the ladder; over this a well oiled cord was passed, at one end of which was the carriage, and at the other the various weights that were employed to drag it. The height of the roof being scarcely 11 feet, I was consequently able to obtain a series of only 3 spaces, adjusted by the law of gravity to 3 equal times. An assistant stood on the roof of the house to manage the carriage, and another sat on the wall head, with a stop watch to count the times, and I was on the ground with a chair and stool at the side of the ladder to enable me to follow the weight in its descent, with my eye and hand exactly level with a particular point marked on the weight, and to touch with chalk the point of the ladder to which the mark on the weight was opposite, at the end of each equal time called by the time-keeper. That the portions of time might be as accurate as possible, I tried twice or thrice, before each experiment, the number of seconds occupied by the weight in descending through the first space of one foot. The experiment was then begun—the time-keeper called sharply " now " as each of the three equal times expired, and at each call I marked with chalk the space described by the weight, in order to ascertain any variation from the law of gravity. I changed frequently the relative power and resistance, but I took no note of the absolute amount of either, for this was nothing to the purpose. It did not answer to allow the power a very great preponderance; for when the times were under two seconds each, they could not be noted with accuracy, nor could I well keep pace with the rapidity of the weight's descent through the last two spaces. These experiments I continued for two days, during upwards of two hours each day; and the results were perfectly satisfactory. The variation from the law of gravity was, when any did exist, always on the side of excess; this amounted, two or three times at the beginning of the first day, to nearly six inches on the whole space described; but on the second day I prevented it, in a great measure, by moving the carriage for some time, and thereby breaking the consistency of the grease on the axles, before the experiments were commenced. After the experiments had been continued for some time, the variation, when any took place, was generally less than I was able to perceive. We have thus one more proof that the friction of wheel carriages is equal in equal times, without respect to their velocity of motion.

I may here notice, that in some experiments made on the friction of railway carriages having fixed axles, it has been found that, when the surfaces of the bearings are small, the friction bears a greater proportion to the weight when such carriages are loaded than when they are empty; this, I think, may readily be accounted for. The rubbing friction of metals has been found never to increase with the extent of surfaces in contact while the weight remains the same; because the greater the surface, the less is the pressure on each point of it. But it is very conceivable, that if the bearing surface of a given weight be reduced beyond a certain degree, a greater indentation and crushing of the obstacles will take place, that the surface will in fact approach more nearly to a sharp instrument; hence are small bearings found to cut grooves in the axles of railway carriages, and to exhibit a greater amount of friction in proportion to the load they support.

I shall now make a few remarks on that sort of friction which I noticed in the text, as being different from the friction produced by mechanical obstacles on surfaces. It is a friction of attrition, but it does not conform to the laws applicable to the others of that kind; for it increases with the velocity and with the extent of rubbing surface. It occurs when various sorts of wood slide upon each other, or when metals slide on wood without having grease applied between the rubbing surfaces; when grease is applied on hard wood, however, as in the boxes of some wheels, the friction is of the same nature as in metals. There is also on woods a greater resistance at the commencement of motion, or an inertia, as it is called, when the surfaces have remained for some time in contact: Coulomb found this in some cases to bear no less a ratio to the resistance after the motion had commenced, than that of 9·5 to 2·2. I have myself found, on placing a block of wood upon a board of uniform smoothness, which was inclined so much as to cause the former to commence a descent by its gravity, that the block of wood had its velocity gradually diminished until its motion finally ceased altogether; then, after an instant, that it would commence moving again, and again gradually stop, and so on.

To account for the increase of friction with the speed of motion on wood, Coulomb adopts the supposition that its surface may be covered with imperceptible "downs." Doctor Brewster seems to adopt the same theory; and says, that the greater the velocity, the greater will be the number of downs opposed to a moving body in a given time: this reasoning would have equal force to prove, that friction increases with the velocity on all surfaces whatever.

The resistance peculiar to surfaces of wood, I am inclined to ascribe to a cause quite distinct from what may be termed any mechanical obstacle. I conceive it to be chiefly of a chemical nature, and to arise either from the affinity of different substances towards each other, or from a tendency to aggregation. Most persons know that dry wood can be set on fire by rubbing, which is a display of chemical affinity or composition; consequently, any degree of rubbing may be supposed to produce a corresponding degree of the same tendency, and oxygen acts as a menstruum of cohesion or